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A Novel Compact Ultra-Wideband Bandpass Filter Using a Microstrip Stepped-Impedance Four-Modes Resonator

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***Abstract* — A novel compact ultra-wideband (UWB) bandpass filter (BPF) using a microstrip stepped-impedance four-modes resonator is developed in this paper. By controlling the resonant frequencies of the first four modes of the resonator, we get four transmission poles within the passband of the filter. Moreover, by enhancing the coupling between the resonator and the input/output feed lines, we obtain two additional transmission poles. As a consequence, we realize a UWB bandpass filter that has six transmission poles in its passband, although only one resonator is utilized. A design method, based on network analysis and optimization in the z-domain, is established to determine the circuit and geometrical parameters of the filter. The measured filtering characteristics of the filter show good agreement with the theoretical predictions and satisfy well the Federal Communications Commission's indoor limit.**

***Index Terms* — Ultra-wideband, bandpass filter, multiple-modes resonator, transmission poles, z-transform.**

I. INTRODUCTION

Microwave filters with wide passband, flat group delay, and sharp attenuations in the stopband are key components in building the ultra-wideband (UWB) communication systems. A number of broadband bandpass filters (BPFs) have been reported [1]-[6] since the Federal Communications Commission (FCC) authorized the unlicensed frequency band 3.1-10.6GHz for UWB applications [7]. In [1]-[3], wideband filters using microstrip dual-mode ring or triangular pathch resonators are proposed and the obtained passband widths are between 20% and 50%. However, these dual-mode resonators are found difficult to achieve a bandwidth over 100%. In [4]-[6], two- and three-modes resonators are proposed, and wideband filters with 3dB fractional bandwidths of about 60% and 100% are realized. The authors of [4]-[6] provided physical explanations of the operation mechanism of the two- and three-modes resonators. However, they failed to develop a systematic design method of this type of filters. In [8], we proposed an accurate and efficient synthesis theory of UWB filters using multi-mode resonators, and validated it by developing a three-degree UWB bandpass filter based on microstrip 3/4 wavelength dual-modes resonators.

In this paper, we propose a novel compact UWB bandpass filter by using a microstrip stepped-impedance four-modes resonator. After deriving the transfer functions of the filter and implementing optimization in the z-domain, we develop a design method of the filter to determine efficiently its circuit and geometrical parameters. In order to avoid critical precision requirement in the fabrication of the filter, we employ aperture-enhanced coupled lines to replace the parallel-coupled lines with very small coupling gaps. The measured frequency response of the fabricated filter exhibits good agreement with the theoretical prediction and satisfies well the FCC's indoor limit.

II. DESIGN METHOD OF THE UWB FILTER

Fig. 1 shows the configuration of our UWB filter using a microstrip stepped-impedance four-modes resonator. The resonator consists of five sections of quarter-wavelength microstrip lines with high and low characteristics impedances. It is coupled with external feed lines through parallel-coupled lines. In the following design, a substrate with a relative dielectric constant of 9.8 and a thickness of 1.27mm is used.

By using an electromagnetic (EM) simulator, Sonnet em [9], we computed the frequency response of the resonator shown in Fig. 1. We find that by appropriately choosing the impedances

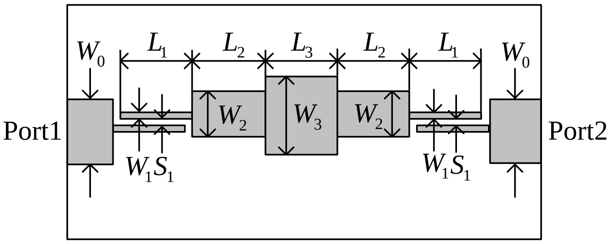


Fig.1. Configuration of a UWB filter using a microstrip stepped-impedance four-modes resonator.

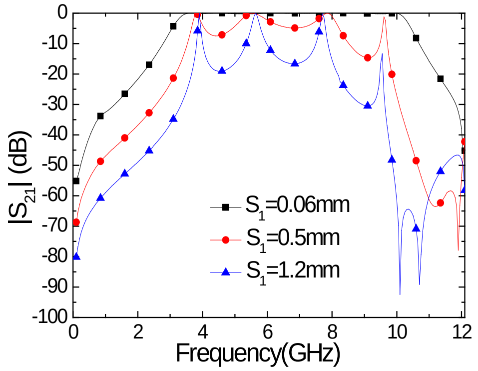


Fig.2. Simulated scattering parameter S_{21} of the four-modes resonator with different coupling gaps S_1 between the resonator and the feed lines. W_0=1.24, W_1=0.24, W_2=3.0, W_3=5.82, L_1=4.35, L_2=3.55, L_3=3.55, all in millimeters.

of the three low-impedance quarter-wavelength microstrip lines, we can allocate the first four resonant modes of the resonator within the passband 3.1-10.6GHz. Fig.2 illustrates the simulated scattering parameter S_{21} of such a resonator with three different coupling gaps (S_1=1.2, 0.5 and 0.06mm) between the resonator and the input/output lines. It is seen that within 3.1-10.6GHz, when the coupling between the resonator and the feed lines is weak (e.g., when S_1=1.2, 0.5), there are four transmission poles produced by the four resonant modes. However, when a strong coupling is enforced by reducing S_1 to 0.06mm, the passband is widened significantly. Actually, two additional transmission poles are realized in the passband, as will be seen clearly from the frequency response of the filter at the end of this section.

We implement the design of the UWB filter in the following three steps [8]. First, we model the filter in Fig. 1 by using cascaded sections of ideal transmission lines with different characteristics impedances, including parallel-coupled transmission lines that represent the coupling sections between the resonator and the input/output lines. After some tedious network analysis, we find that the filter can accomplish Chebyshev filtering characteristics and its ideal transfer function is deduced as follows [8]

$$\left|S_{21}(\theta)\right|^2 = \frac{1}{1+\varepsilon^2 F^2(\theta)} \qquad (1)$$

here ε is the passband ripple constant, θ is the electrical length of the cascaded transmission lines, and $F(\theta)$ is a characteristic function given by

$$\mathrm{F}(\theta) = \frac{\left(\sqrt{\cos^{-2}(\theta_c)-1} - \cos^{-1}(\theta_c)\right) \bullet \cos(\theta) T_5\left(\frac{\cos(\theta)}{\cos(\theta_c)}\right) + T_6\left(\frac{\cos(\theta)}{\cos(\theta_c)}\right)}{\sin(\theta)} \qquad (2)$$

where θ_c is the electrical length at the lower cutoff frequency of the filter, $T_n(x)=\cos(n\cos^{-1}x)$ is the Chebyshev function of the first kind of degree n. By conducting a z-transform of (1) using

$$j\tan\theta = (1-z^{-1})/(1+z^{-1}) \quad (z = e^{j2\theta}) \qquad (3)$$

we get the ideal transfer function $S(z)$ of the filter in the z-domain [8][10][11].

Next, we derive the wave transmission matrices of the parallel-coupled transmission lines and the unit elements (i.e., transmission lines of electrical length θ) in the z-domain, and multiply these matrices in sequence to get a transfer function *T(z)* of the filter in terms of the characteristic impedances of each of the transmission line sections shown in Fig. 1, including the even- and odd-mode characteristic impedances of the parallel coupled lines [8][10][11].

Finally, by minimizing the difference between the ideal transfer function *S(z)* and the transfer function *T(z)* using an optimization algorithm [8][10][11], we get the characteristic impedances of each transmission line sections of the filter shown in Fig. 1.

As an example, we design a filter having a midband frequency of 6.85GHz. The equal-ripple fractional bandwidth is 100%. This means that the electrical length of each transmission line sections of the filter is θ_c=45° at the lower cutoff frequency. The passband ripple constant ε in (1) is chosen as 0.15. Following the above described design procedure, we obtain the characteristic impedances of the three low-impedance transmission lines of the resonator in Fig.1 as 30.9, 19.5, and 30.9Ohm, respectively. The even- and odd-mode characteristic impedances of the parallel-coupled lines are 37.0 and 141.5 Ohm, respectively. The geometrical dimensions of the filter are then obtained by using Sonnet em, and are given in Table1, where W_0, W_1, W_2, W_3 denote the widths of each transmission lines shown in Fig. 1, L_1, L_2, L_3 are their lengths, and S_1 the gap between the resonator and the input/output feed lines.

Fig. 3 provides a comparison of the frequency responses of the designed UWB filter. The solid lines are theoretical results calculated from the ideal transfer function (1) of the filter, and the broken lines are simulated response of the filter in

Table1. Dimensions of the proposed UWB filter shown in Fig.1

W_0	W_1	W_2
1.24mm	0.24mm	3mm
W_3	S_1	L_1
5.82mm	0.06mm	4.35mm
L_2	L_3	
3.55mm	3.55mm	

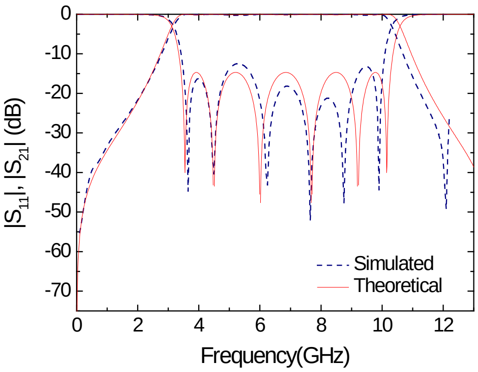


Fig.3. Comparison of the frequency responses of the UWB filter. The solid lines are theoretical results calculated from the ideal transfer function (1) of the filter, and the broken lines are simulated response of the filter shown in Fig. 1 by using an electromagnetic simulator.

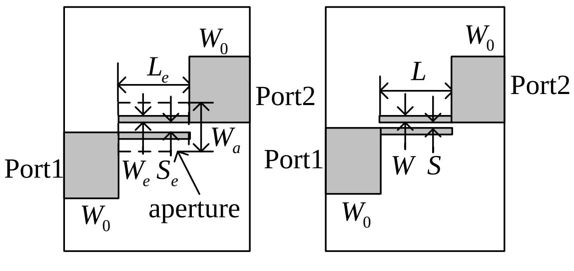
microstrip form by using Sonnet em. A very good agreement is found. In the passband, six transmission poles are observed, among which, four are produced by the first four resonant modes of the resonator and the others are contributed by the strong coupling between the resonator and the input/output parallel-coupled lines.

III. MODIFICATION AND EXPERIMENTAL VERIFICATION

As given in Table1, the gap S_1 between the resonator and the input/output feed lines in Fig. 1 is merely 0.06mm. Such a small dimension will enforce critical tolerance requirement in the fabrication of the filter. In order to alleviate the precision requirement and reduce thereby the fabrication cost, we use aperture-enhanced coupled lines, as shown in Fig.4 (a), to replace the simple parallel-coupled lines in the filter designed above. The aperture-enhanced coupled lines are designed to have almost the same frequency response as that of the parallel-coupled lines, as shown in Fig. 4(b), over a wide frequency band. This design is accomplished by using Sonnet em, and the obtained dimensions of the aperture-enhanced coupled lines in Fig. 4(a) are: W_{1e}=0.29, S_{1e}=0.1, L_{1e}=4.4, W_{1a}=1.59, all in millimeters. A comparison of the EM simulated frequency responses of the parallel-coupled lines and the aperture-enhanced coupled lines is given in Fig. 5, and a very good agreement is found over 1-12GHz.

After replacing the parallel-coupled lines in the filter with the aperture-enhanced coupled lines, the configuration of the modified UWB filter is shown in Fig. 6. The dimensions W_{2e}, W_{3e}, L_{2e} and L_{3e} are adjusted to 2.91mm, 5.63mm, 3.6mm, and 3.55mm, respectively. A photograph of the fabricated UWB filter is given in Fig. 7, and it is seen that the filter is very small.

The frequency response of the filter is simulated by using Sonnet em, and measured by employing a network analyzer HP8510C. Fig. 8 provides a comparison of the simulated (solid lines) and measured (broken lines) characteristics of the filter, and a good agreement is observed over the wideband of



(a) (b)

Fig.4. (a) Aperture-enhanced coupled lines. An aperture of L_e x W_a is formed on the backside ground of the substrate. (b) Parallel-coupled lines.

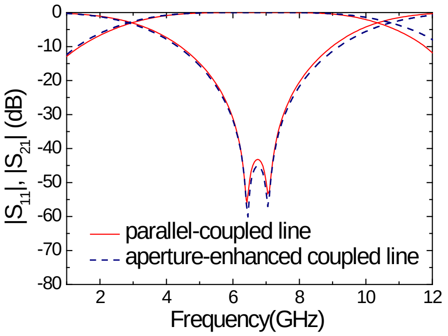


Fig.5. EM simulated frequency responses of the parallel-coupled lines and its equivalent aperture-enhanced coupled lines.

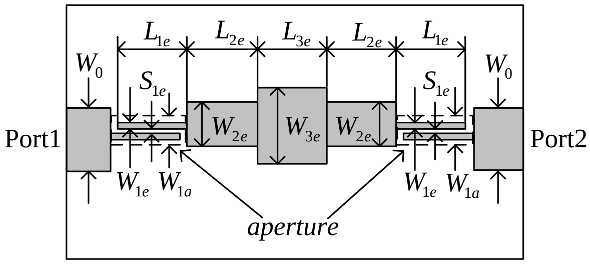


Fig.6. Configuration of a UWB filter using a microstrip stepped-impedance four-modes resonator and aperture-enhanced coupled lines. Two apertures of L_{1e} x W_{1a} are formed on the backside ground of the substrate.

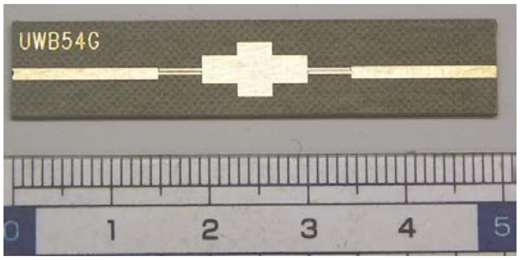


Fig.7. Photograph of the fabricated UWB filter using a microstrip stepped-impedance four-modes resonator and aperture-enhanced coupled lines. Two apertures are formed on the backside ground of the substrate.

measurement. At most frequencies within the passband, the measured insertion loss of the filter is better than 1dB and the return loss greater than 12dB.

In Fig.9, the FCC's indoor limit is drawn for comparison with the simulated and measured frequency responses of the UWB filter described above. The comparison indicates that over 1-12 GHz, the FCC's indoor limit is satisfied at most frequencies.

Fig. 10 shows the simulated group delay of the filter by using Sonnet em. It is seen that within the passband, the simulated group delay is less than 0.7ns.

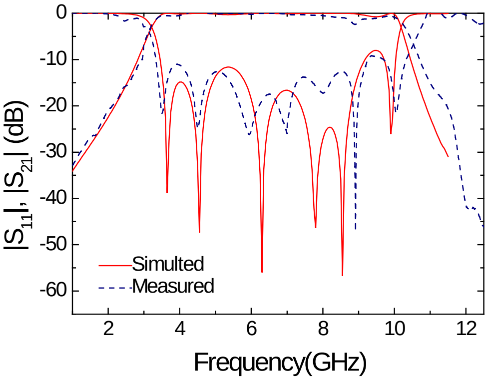


Fig. 8. Comparison of the simulated and measured frequency responses of the UWB filter shown in Fig. 6.

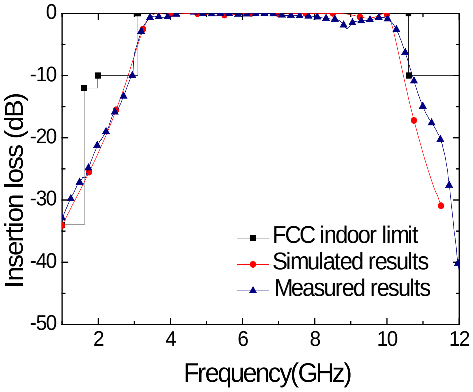


Fig.9. Comparison of the FCC's indoor limit with the simulated and measured frequency responses of the UWB filter of Fig. 6.

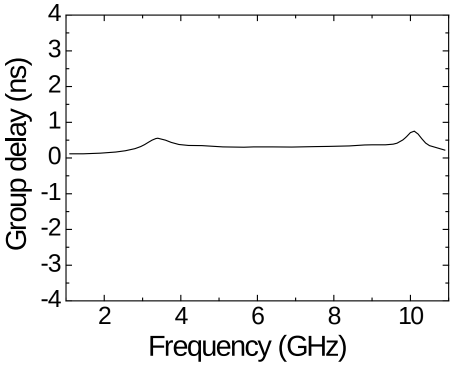


Fig.10. Simulated group delay of the UWB filter shown in Fig. 6.

IV. CONCLUSION

A novel UWB bandpass filter using a microstrip stepped-impedance four modes resonator is proposed, and its design method is developed. Because only one multi-mode resonator is used, the filter is compact in size and low-loss in the passband. Six transmission poles are obtained in the passband, and a wide passband is realized with flat group delay. By replacing the parallel-coupled lines in the filter with the aperture-enhanced coupled lines, a moderate fabrication precision is allowed to realize the filter. A good agreement is found between the theoretical and measured responses of the filter. The FCC's indoor limit is satisfied over a very wide frequency band.

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